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An Overview of the NASA Aviation Safety Program Propulsion Health Monitoring Element

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AN OVERVIEW OF THE NASA AVIATION SAFETY PROGRAM PROPULSION HEALTH MONITORING ELEMENT

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Abstract

The NASA Aviation Safety Program (AvSP) has been initiated with aggressive goals to reduce the civil aviation accident rate. To meet these goals, several technology investment areas have been identified including a sub-element in propulsion health monitoring (PHM). Specific AvSP PHM objectives are to develop and validate propulsion system health monitoring technologies designed to prevent engine malfunctions from occurring in flight, and to mitigate detrimental effects in the event an in-flight malfunction does occur. A review of available propulsion system safety information was conducted to help prioritize PHM areas to focus on under the AvSP. It is noted that when a propulsion malfunction is involved in an aviation accident or incident, it is often a contributing factor rather than the sole cause for the event. Challenging aspects of the development and implementation of PHM technology such as cost, weight, robustness, and reliability are discussed. Specific technology plans are overviewed including vibration diagnostics, model-based controls and diagnostics, advanced instrumentation, and general aviation propulsion system health monitoring technology. Propulsion system health monitoring, in addition to engine design, inspection, maintenance, and pilot training and awareness, is intrinsic to enhancing aviation propulsion system safety.

Introduction

The NASA Aviation Safety Program (AvSP) has been initiated with aggressive goals to reduce the civil aircraft accident rate.[1,2] The AvSP supports the national goal of reducing the fatal accident rate for aviation by 80 percent in 10 years, and a longer term NASA goal of reducing the aircraft accident rate by 90 percent in 25 years. The worldwide commercial aviation major accident rate (as judged by hull losses per million departures) has been nearly constant over the past two decades.[3] Although the rate is low, increasing traffic over the years has resulted in the absolute number of accidents also increasing. Given the projected future increases in air travel demands, the number of aviation accidents will continue to climb if no improvement in the accident rate is made (see Figure 1). Given the very visible, damaging and tragic effects of even a single major accident, this increase in the number of accidents would clearly have an unacceptable impact upon the public's confidence in the aviation system and impede the anticipated growth in commercial air travel.

Past technology advances have resulted in aircraft propulsion systems with excellent safety and reliability records. However, propulsion system malfunctions still contribute to a number of aircraft accidents and must be addressed to meet the aggressive goals set forth by the AvSP. As part of the AvSP, several technology investment areas have been identified to improve overall aviation safety including propulsion system health monitoring. An Aviation Safety Program Organization chart is shown in Figure 2. Propulsion Health Monitoring (PHM) is a Level 4 sub-element led out of the NASA Glenn Research Center under this Program. Specific objectives of this sub-element are to develop and validate propulsion system health monitoring technologies designed to prevent engine malfunctions from occurring in flight and to mitigate detrimental effects in the event an in-flight malfunction does occur.

Aviation Propulsion System Safety Issues

A review of available aviation propulsion system safety information was conducted to help prioritize PHM areas to focus on under the AvSP. The Aerospace Industries Association (AIA) Propulsion Committee (PC) on Continued Airworthiness Assessment Methodology conducted an analysis of aircraft propulsion system safety hazards over a ten year time period.[4] This study included transport category aircraft data from turboprop, low bypass, and high bypass turbofans. Data was categorized into Level 4 events (defined as severe consequences such as

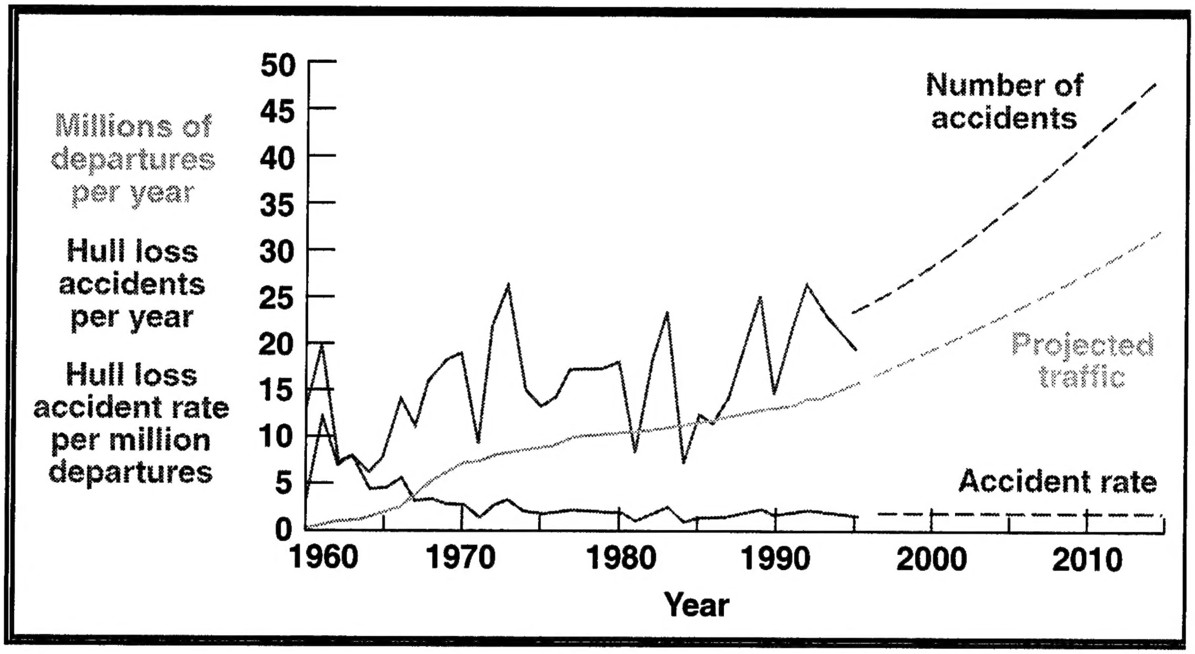

Figure 1. Projected Safety Scenarios (Source: The Boeing Company)

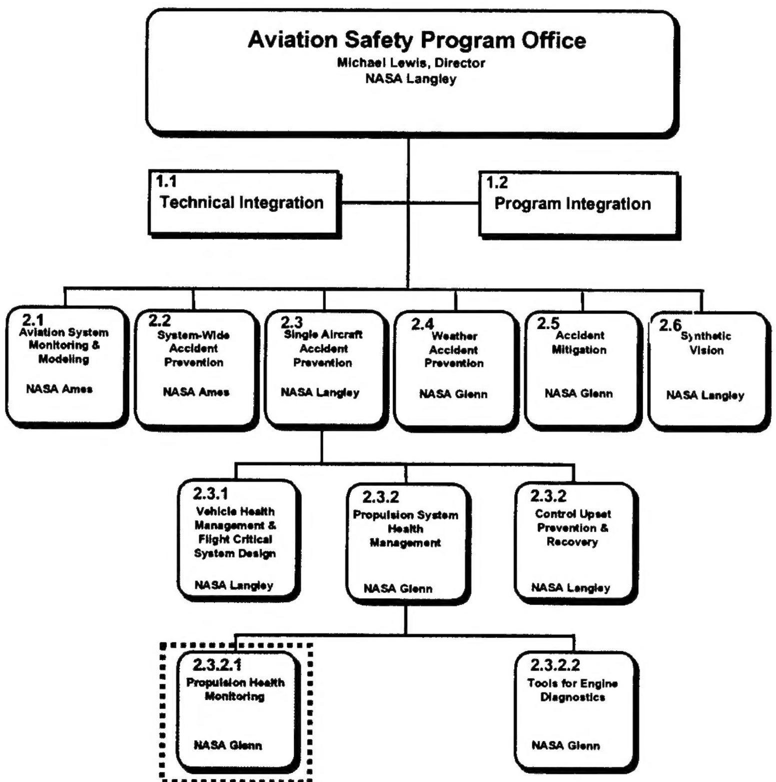

Figure 2. NASA Aviation Safety Program

forced landings, hull loss, serious injuries or fatalities), and Level 3 events (defined as serious consequences such as substantial aircraft damage, rapid depressurization, permanent loss of thrust on multiple engines, and impairment of aircraft controllability). This study found that a Level 4 propulsion system related event occurred 4.21 times per 10 million aircraft flights, and a Level 3 event occurred 6.22 times per 10 million flights. To put these numbers in perspective, a recent study found that the propulsion system contributed to approximately 12% of all jet transport accidents.[5] The top two event categories, uncontained failures (18% of propulsion-related Level 3&4 events) and propulsion system malfunction plus crew error (15% of propulsion-related Level 3&4 events), are further discussed below.

Uncontained Failures

Uncontained turbine engine rotor failure is an event that results in the escape of debris through (out of) the engine nacelle envelope due to a rotating component failure. This uncontained release of debris can cause catastrophic damage to the aircraft structure and systems, negatively impacting the controllability of the vehicle, and/or serious injury or fatalities to the vehicle occupants. There are a variety of potential initiating causes for uncontained turbine engine rotor failures such as shop maintenance and overhaul errors, material or manufacturing defects, low cycle fatigue, foreign object damage, and mechanical component malfunctions. Uncontained engine events were involved in 2.2% of all fatalities in fixed wing civil aviation accidents during the period 1984 through 1989.[6]

Under the NASA AvSP, health monitoring technologies for in-situ crack detection will be developed and evaluated. The goal is to reduce uncontained engine failures by providing both continuous monitoring of critical engine components and a prognostic capability to detect cracks prior to propagation to failure. These technologies will be further discussed later in this paper.

Propulsion System Malfunction Plus Inappropriate Crew Response

Due to the steady improvements in reliability made by the aviation community, catastrophic engine failures have become rare. Today, propulsion-related aviation accidents are often not due solely to malfunctions of the propulsion system, but rather to a number of contributing factors. For example, an aviation accident or incident may occur when a single benign propulsion system malfunction, not normally considered safety significant, occurs coupled with the pilots' inappropriate or lack of response to the malfunction. Such an event, termed Propulsion System Malfunction Plus Inappropriate Crew Response (PSM+ICR), is now the dominant contributor to turbofan and turboprop aircraft Level 4 propulsion-related events.[4]

Recently, the Aerospace Industries Association (AIA) and the European Association of Aerospace Industries (AECMA) jointly formed a working group to study and assess the causes and contributing factors in PSM+ICR accidents and incidents. Published documentation from this joint effort summarizes their findings, conclusions, and recommendations for potential corrective action.[7] Turbofan aircraft data analysis identified four major categories of PSM+ICR events: (1) rejected takeoffs at or above V1 (takeoff decision speed) following compressor surge/stall, severe vibration, or warning lights, (2) loss of control resulting from undetected thrust asymmetry and/or aerodynamic cues often masked by auto-throttle/auto-pilot, (3) shutdown or throttle pull-back of a good engine due to incorrect flight crew diagnosis or incorrect action following correct diagnosis, and (4) other events such as difficulty isolating a malfunctioning engine, or the failure to recognize the need to take corrective action. Recommendations from this study include critical needs to enhance flight crew training and awareness in recognizing and responding to propulsion system failures, to ensure that flight simulators used to support pilot training have realistic propulsion system malfunction simulation capability, and to review current propulsion system cockpit instrumentation requirements to determine if improved engine displays or methods can be found to better aid the flight crew in recognizing propulsion malfunctions. Under the NASA AvSP, health monitoring technologies will be developed and evaluated to reduce the root causes of propulsion malfunctions such as surge/stall, asymmetric thrust, and in-flight engine shutdowns that can lead to PSM+ICR events.

General Aviation

In addition to focusing on commercial transport aircraft safety, the NASA AvSP will also attend to general aviation safety. With the general aviation market poised to grow significantly in future years, safety concerns must be removed as a barrier if this growth is to be realized. Accident data from the Nall Report for the year 1998 attributes 6.3% of all general aviation accidents and 2.1% of fatal general aviation accidents to engine and propeller mechanical/maintenance problems.[8] Another 2.4% of all general aviation accidents and 2.1% of fatal general

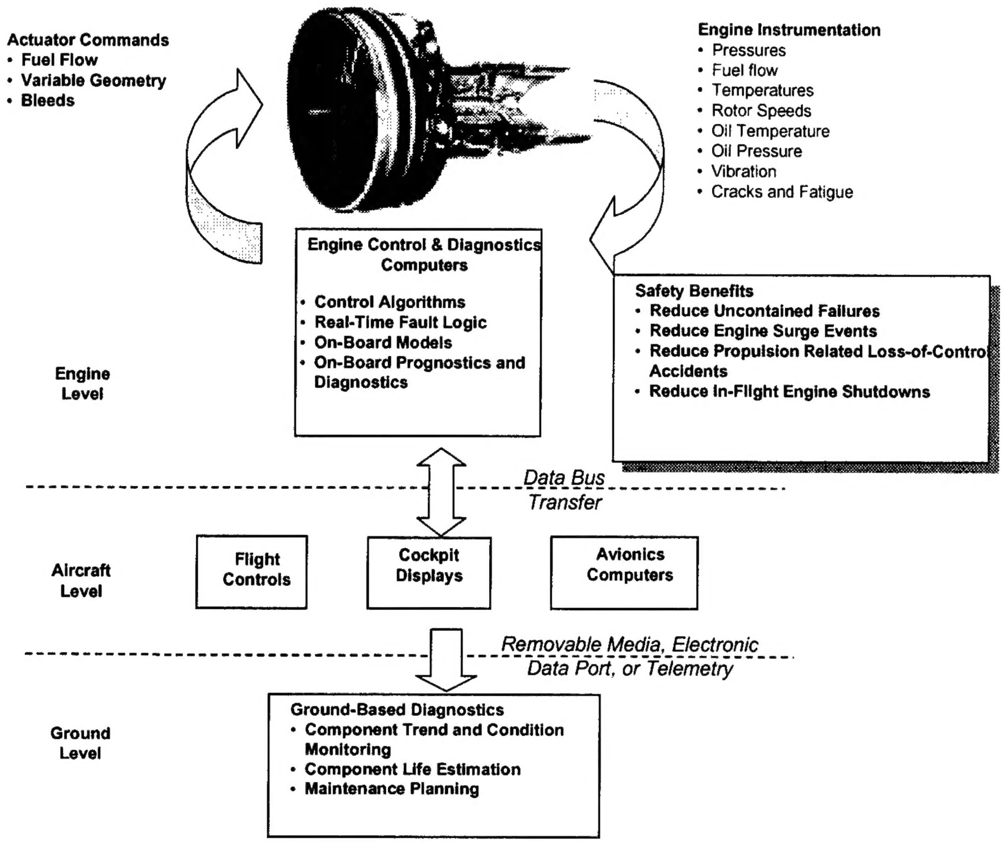

Figure 3. Propulsion System Health Monitoring Architecture

aviation accidents were related to fuel system anomalies. This report also noted the role human error plays in fuel mismanagement, maintenance, and incorrect operating procedures when system failures occurred, once again highlighting the fact that engine malfunctions are often just one of several contributing causes leading to an accident. The NASA AvSP is also working towards the development of health monitoring technologies specific to general aviation engines.

Propulsion System Health Monitoring Challenges

Aircraft engine health monitoring techniques have been in place for several decades and have yielded a variety of benefits including improved aircraft safety and reliability, reduced engine maintenance time and cost, and reduced unscheduled engine maintenance or removals. Future advances in these areas hold much promise for additional aircraft safety and economic enhancements. Engine health monitoring is the assessment of the engine's physical condition by monitoring and interpreting available engine instrumentation readings and operating cycles (see Figure 3.) Such a process can often detect incipient engine trouble well in advance of serious anomalies.

Historically, in-flight engine monitoring has been a flight engineer/pilot task through the visual and tactile cues available on cockpit gages and controls. Ground-based engine monitoring capabilities have progressed over the years. On early generation aircraft, which lacked automatic data acquisition systems, engine data was recorded manually by the flight crew and later fed into a computer for trend analysis. On modern aircraft, engine performance data is automatically recorded and transferred to ground station for analysis either manually or through satellite or ARINC ground link transmission. Future trends are towards an increase in the sophistication of on-board and ground-based engine monitoring and maintenance systems including dedicated on-board diagnostic processors and algorithms, advanced diagnostics and prognostics instrumentation, and the integration of diagnostic information with fault accommodating control logic. The ultimate vision is a combined monitoring system that applies prognostics within an engine health management system to allow aircraft operators to automatically track remaining life of

engine components.[9,10] Such information will enhance operational safety and allow the optimal scheduling and performance of engine maintenance.

The PHM technologies to be developed under the NASA AvSP are primarily focusing on civil aviation safety issues. However, to a large degree it will be the secondary economic benefits which help this technology gain acceptance by the aviation industry. Benefits include reduced inspection time, reduced maintenance costs, reduced unplanned engine maintenance, reduced operating costs, extended time before overhaul, and optimized maintenance scheduling and management of inventory.

The engine manufacturers, airlines, and regulatory agencies recognize these safety and economic benefits and have worked jointly to define and implement current engine inspection and health monitoring programs. NASA's strategy will be to work with these organizations to define, develop, and integrate AvSP health management technologies into existing engine monitoring programs. Any additional benefits to be gained from the incorporation of new health management technology into the aviation system will be weighed against any added cost. This includes not only initial procurement cost, but also considerations of weight, reliability, and operating costs to maintain the new technology. The false alarm and missed detection rates of the technology are also critical. Missed detections can be detrimental in terms of both cost and safety. False alarms, in addition to increasing costs and causing interruptions in aircraft availability, can also have a negative impact on safety by causing unnecessary inspections and maintenance. For example, recent studies indicate that maintenance error accounts for nearly 1/3 of all aircraft engine in-flight shutdowns and that the probability for maintenance error needs to be considered when determining the requirement for and frequency of inspection and replacement programs.[11] Also, care must be taken to ensure that any advanced fault accommodating control logic technology incorporated does not compromise the flight crews' ability to recognize and respond to a malfunctioning engine by eliminating cockpit cues.

AvSP Propulsion Health Monitoring Planned Activities

The NASA AvSP Propulsion Health Monitoring element has work ongoing in several technology areas including vibration diagnostics for disk crack detection, model-based controls and diagnostics, component stability monitoring, advanced instrumentation, and general aviation PHM technology. These technologies are discussed in the following sections.

Vibration Diagnostics

As described earlier, uncontained engine failure is an aviation safety concern. Under the AvSP, NASA and General Electric Company are jointly working to develop and validate an on-line, automated crack-detection system capable of detecting turbine rotor disk cracks in early stages through the noninvasive monitoring of vibration measurements. Analytical models of the disk assembly will be used to correlate the size and location of disk cracks to the vibration signature along the rotor support structure. The diagnostic technique is based on discerning the additional mass-unbalance effect caused by the opening of a crack. When a radial/axial disk crack develops, it tends to open with speed due to the stresses induced by centrifugal loading. The resulting change in the distribution of the disk mass causes a shift in the phase and the amplitude of the once-per-rev unbalance vector versus a previously established baseline as shown in Figure 4. Advanced signal processing techniques based on the modeled signature will be applied to the vibration measurements taken from the bearing-mounted radial vibration accelerometers to detect and monitor the propagation of disk cracks prior to their growth to a critical size. Initial efforts will focus on technology validation on component subscale and full scale rig testing conducted in spin facilities. A baseline vibration signature for an unflawed disk will be established by collecting data over a specified speed range of the component. A crack will then be introduced into the disk, and once again vibration data will be collected over the specified speed range. The crack will be progressively enlarged, and the test will be repeated. The detection algorithm will be evaluated for sensitivity (minimum detectable crack size) and robustness to distinguish disk cracks from other engine faults that may produce similar symptoms. Follow on efforts will mature the technology for implementation and certification in a commercial engine product.

Similar technology has been successfully applied to the detection of disk cracks in land-based gas turbine engines and aircraft engine disks undergoing spin pit testing.[12] Critical work is needed in modeling, instrumentation, and signal processing to advance and incorporate this technology into an on-board aircraft engine vibration monitoring system.

Although disk crack detection is the focus of this effort, there are additional benefits of enhanced on-board aircraft gas turbine engine vibration monitoring

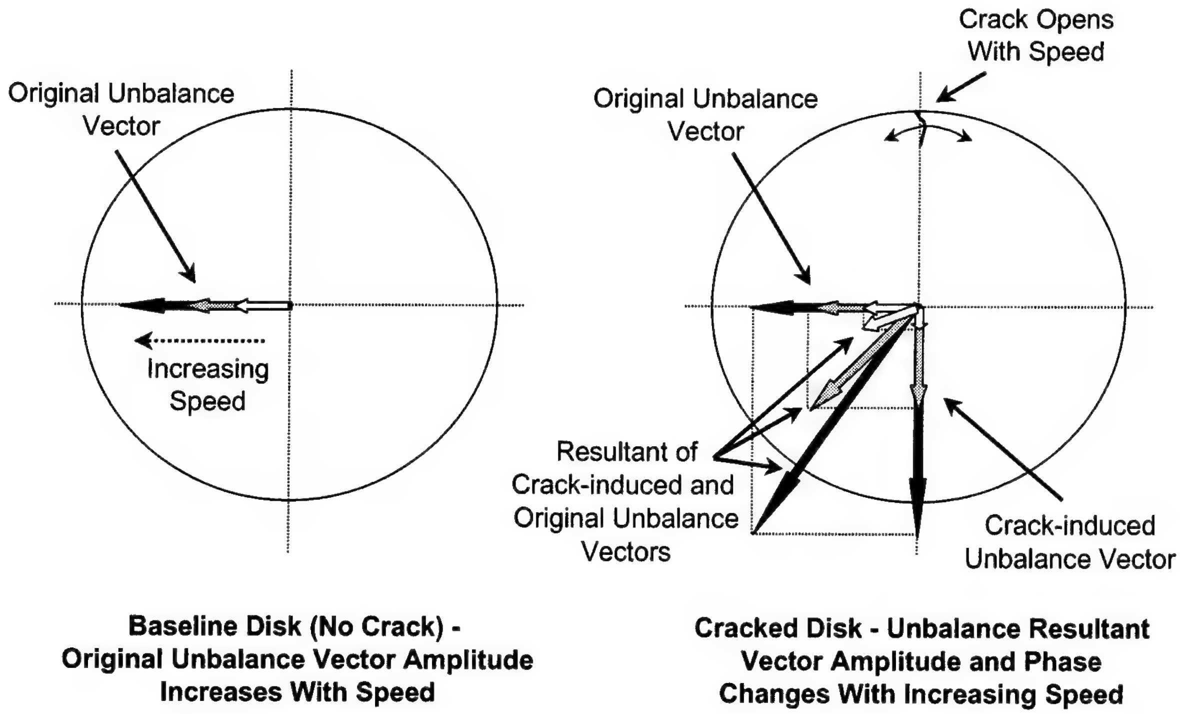

Figure 4. Disk Crack Detection Unbalance Method

(EVM) systems. For example, enhanced EVM systems can enable the early detection and prevention of anomalies such as bearing degradation, blade loss/rubbing, and rotor unbalance. EVM prognostic capabilities will allow aircraft operators to optimize the scheduling and performance of engine maintenance, reduce the occurrence of unscheduled maintenance, eliminate more substantial and costly failures, and reduce ground-based inspection time. These collective safety and economic benefits will help to accelerate industry acceptance and incorporation of this technology.

Model-Based Controls and Diagnostics

Model-Based Controls and Diagnostics (MBCD) consists of a real-time on-board aerothermodynamic engine model incorporated into the engine control architecture as shown in Figure 5. An on-line parameter estimation algorithm, or tracking filter, tunes the model to estimate off-nominal engine component performance, sensor bias, or actuator bias. Such an architecture provides several benefits including continuous real-time trending of engine health, synthesized sensor values which can be used in sensor validation logic, and estimates of unmeasurable engine parameters such as thrust and component stability margins which can be used in feedback control logic. Aircraft operators have used model-based gas turbine engine condition monitoring systems in ground-based applications for several decades to trend engine performance from recorded engine measurements.[13,14,15,16] More recently, adaptive on-board engine models have been demonstrated for use in real-time engine performance monitoring and optimizing engine control to accommodate off-nominal engine behavior.[17,18,19,20,21,22] This has been enabled by the increased processing capability of today's microcomputers.

Under the AvSP, MBCD technology will be extended to provide prognostic and diagnostic capability and fault accommodation in the propulsion system, thereby preventing or reducing the severity of potentially safety-significant failures. The aviation safety concerns include the loss of control, controlled flight into terrain, or rejected takeoffs caused by the pilot's incorrect response to these engine malfunctions. An initial effort will focus on the collection and analysis of information on current in-flight engine shutdowns, engine related aborted takeoffs, engine overspeed/overthrust, engine surge/stall, and multi-engine combustor blowout events and their underlying causes. After these events have been analyzed, they will be classified into fault types. From this classification several faults will be selected for further study based on associated frequencies of occurrence and the potential to be detected and accommodated by MBCD technology.

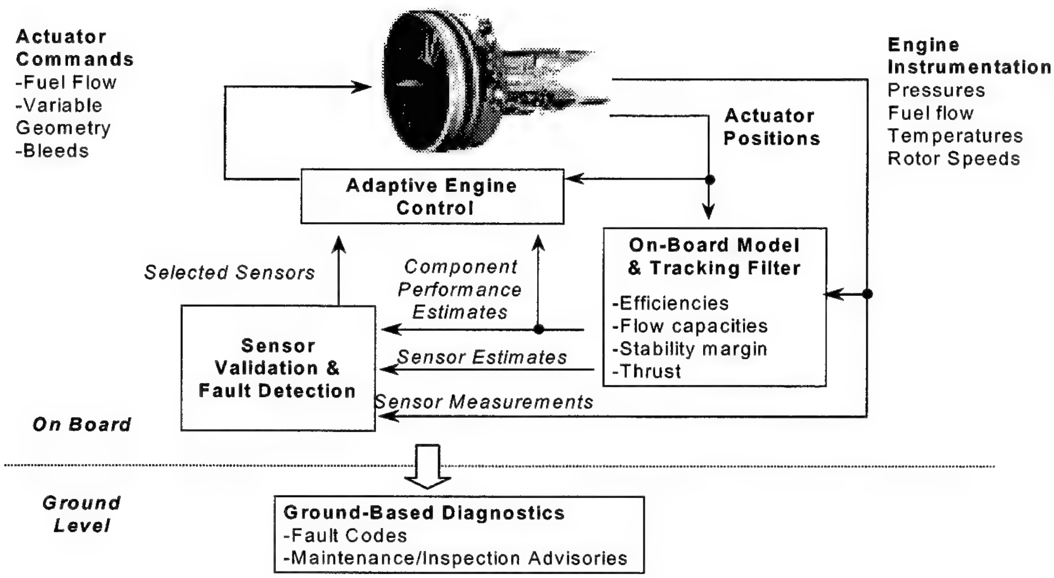

Figure 5. Model-Based Controls and Diagnostics Architecture

MBCD is a promising technology for accommodating engine faults such as sensor failures, actuator failures, and moderate gas-path component damage, and the effects such faults/degradation have on component operability margins. The estimation and control of component operability margins through MBCD can reduce the occurrence of potentially safety-significant malfunctions such as engine surge. Initially, selected engine failures will be modeled in a simulation environment and the diagnostic and control logic will be evaluated. The results of the simulation evaluation will be analyzed to quantify the benefits in terms of reduction of engine malfunctions, and a study will be performed to recommend control and diagnostic strategies for further development and maturation. Critical to the performance of a MBCD architecture is the accuracy of the tracking filter to tune the on-board model to match the performance of the actual engine. Candidate tracking filter parameter estimation techniques include weighted least squares, extended Kalman filters, neural networks, and genetic algorithms. A challenge is that the system is typically underdetermined, i.e. there are more unknown system diagnostic parameters than equations. To make the problem manageable, past efforts have placed restrictions on the number of unknowns to be estimated or performed multi-point tracking, leveraging the non-linearity of the system to allow additional unknowns to be estimated.[23] Under the AvSP, MBCD tracking filter logic will be evaluated for accuracy and robustness in detecting and preventing safety-significant engine malfunctions.

The emphasis of this activity is to prevent in-flight shutdowns and engine surge events in order to enhance propulsion safety. However, a continuous on-board monitoring system provides additional economic benefits. For example, early detection of incipient failures can prevent more costly failures from occurring, and can reduce the unplanned maintenance and engine removals. Adaptive control schemes have the additional benefit of optimizing fuel efficiency or extending component life.

Component Stability Monitoring

As indicated previously, compressor stall is often a contributing factor in turbofan aircraft PSM+ICR accidents and incidents. In addition to the MBCD techniques described above, the AvSP will also investigate the diagnosis of component health through the interpretation of high response pressure measurements. The activity leverages past first principle component stability modeling developments advanced under theoretical studies of the rotating stall inception process and active stall control in axial flow

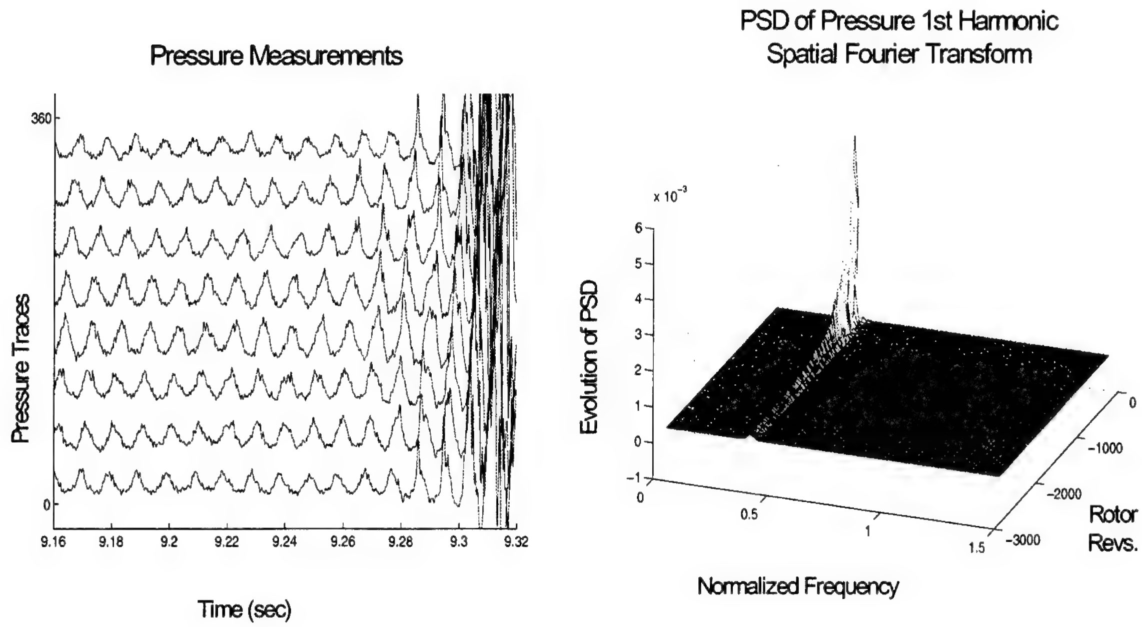

Figure 6. Time History of Pressure Measurements and Evolution of Pressure Power Spectral Density Prior to Surge Event

compressors.[24,25,26] This work has demonstrated the existence of small amplitude pressure waves rotating about the circumference of the compressor prior to rotating stall inception (see Figure 6). The traveling wave energy and frequency content varies with rotor speed. A past study has demonstrated good agreement between analytical models and experimental data in analyzing the pre-stall behavior of several high speed compressors.[27] This work also highlighted that modes are susceptible to excitation by geometric nonuniformities in the compressor.

There can be numerous causes for degraded compressor stability margin in a gas turbine engine such as component degradation, manufacturing variation, control system variations, and airflow distortion. Past work has found that deteriorated compressors exhibit larger amplitude static pressure stall precursor waves than undeteriorated compressors during transient operation.[28] This was demonstrated experimentally by comparing the power spectral density time evolution of compressor static pressure measurements collected from an undeteriorated and a deteriorated engine. These experimental results showed good agreement with the analytical dynamic stall inception model.

The AvSP will further investigate the use of component traveling wave energy as a real-time measure of compressor stability. Available empirical compressor data will be evaluated to determine the change in traveling wave energy with varying rotor speed and stall margin.

Advanced Instrumentation

The objective of this activity is to develop and demonstrate robust and affordable engine crack detection instrumentation for operation within harsh, high temperature engine environments. The developed instrumentation will be applicable to a variety of engine components including disks, shafts, blades, vanes, and support structures for a full field, real-time and in-situ measurement. The goal is to enhance propulsion safety through the reduction of uncontained engine failures and in-flight shutdowns. Past technology developments to be leveraged and advanced include high temperature thin film sensors[29] (see Figure 7), smart coatings[30], and ultrasonic piezoelectric transducers.[31] The approach will be to develop and demonstrate this instrumentation and its associated signal conditioning software in component rig tests followed by an on-engine demonstration. The on-board implementation of such technology would enable continuous real-time monitoring and allow detection of the initiation and propagation of cracks on the order of one mil in width. On-board signal

processing requirements will be defined. Wireless data transmission will also be explored.

In addition to the safety benefits of crack detection, this advanced instrumentation would also provide measurements of structural strain and component temperature to 1000 °C. Once available, these measurements can enhance life usage monitoring and life extending control applications yielding economic benefits of extended component time before overhaul.

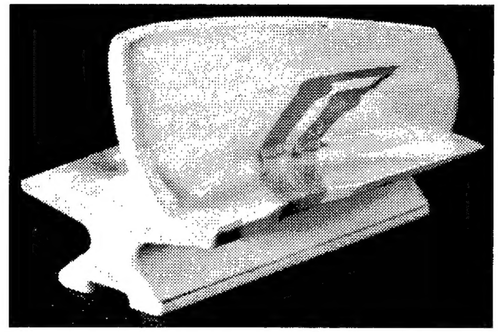

Figure 7. Blade-Mounted High Temperature Thin Film Strain Gauge

General Aviation Propulsion System Health Monitoring

The NASA AvSP is also focusing on affordable propulsion health monitoring technologies for general aviation (GA) aircraft to enhance safety. Past GA PHM has been limited, often relying on the pilot to manually monitor engine health through cockpit instrumentation and scheduling preventative maintenance on a fixed-time basis. Safety and economic improvements are possible by automating the process of recording, processing, and trending engine instrumentation. Challenges include making the technology light-weight and affordable to allow feasible implementation. Specific AvSP plans include the development and evaluation of robust low-cost combustion pressure instrumentation for piston-powered general aviation aircraft. This will provide real-time combustion process feedback that can be used for enhanced diagnostics and control applications. The development and demonstration of a low-cost engine monitoring and diagnostic system for GA aircraft is also planned. This passive monitoring system will collect and trend a variety of engine parameters. The system will archive and interpret the parameters providing maintenance and pilot advisories regarding the condition of the engine.

Related Activities

PHM is one of several technology investment areas that can help to enhance aviation propulsion system safety. This activity will leverage synergistic work in the areas of system design, human factors, inspection, and maintenance procedures. Some of these technologies are further discussed below.

Engine material and structural design advancements can yield improved crack resistant materials to reduce engine failures and enhanced lightweight engine containment systems to withstand the physical forces of fragmented engine components in the event of an engine failure. The NASA UltraSafe Engine program is addressing such material and structural improvements. Enhanced engine inspection techniques are also needed. Component life prediction models and non-destructive evaluation techniques will be developed and integrated to demonstrate enhanced component inspection capabilities both within maintenance and overhaul facilities and on-wing under the NASA AvSP Tools for Engine Diagnostics sub-element. Enhancing the flight crews ability to properly recognize and respond correctly to propulsion system malfunctions is also critical. An industry effort has been initiated to improve the way flight simulators portray engine problems in an attempt to avoid conditioning pilots to react in ways that could turn minor malfunctions into in-flight emergencies.[32] Efforts continue in the area of data mining to examine operational engine data and overhaul data to gain improved understanding of the factors which influence how aircraft engines age and accumulate damage.[33] This information will help to define improved engine operation procedures and health monitoring techniques. A wealth of propulsion health management research is currently ongoing. Within the AvSP, work in Rotorcraft Health and Usage Monitoring is being conducted under a separate element. This work focuses on monitoring the health of rotorcraft gear and transmission systems. The U.S. Department of Defense has a variety of ongoing activities in aircraft gas turbine engine health management research, including activities under the Joint Strike Fighter Program, which is focusing on reducing engine maintenance costs and ensuring reliable operation for single engine aircraft.

Collective advances in these technology areas will enhance aviation propulsion system safety and support the achievement of the national and the NASA aviation accident reduction goals.

Summary

Propulsion Health Monitoring (PHM) is needed in concert with system design, flight crew training, inspection, and maintenance procedures to collectively enhance aviation propulsion system safety. There is a need for continued study of propulsion related accident and event data to identify underlying root causes for malfunctions and to develop improved fault models for diagnostic and prognostic applications. Continued attention to economic factors including weight, cost, robustness, and reliability is also necessary. The vision of the NASA Aviation Safety Program Propulsion Health Monitoring sub-element is to incorporate new PHM technology such as enhanced vibration diagnostics, model-based controls and diagnostics, component stability monitoring, advanced instrumentation, and affordable general aviation PHM technology into an overall architecture that allows enhanced safety in addition to optimized operation and management of fleet assets.

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13. ABSTRACT *(Maximum 200 words)*

The NASA Aviation Safety Program (AvSP) has been initiated with aggressive goals to reduce the civil aviation accident rate. To meet these goals, several technology investment areas have been identified including a sub-element in propulsion health monitoring (PHM). Specific AvSP PHM objectives are to develop and validate propulsion system health monitoring technologies designed to prevent engine malfunctions from occurring in flight, and to mitigate detrimental effects in the event an in-flight malfunction does occur. A review of available propulsion system safety information was conducted to help prioritize PHM areas to focus on under the AvSP. It is noted that when a propulsion malfunction is involved in an aviation accident or incident, it is often a contributing factor rather than the sole cause for the event. Challenging aspects of the development and implementation of PHM technology such as cost, weight, robustness, and reliability are discussed. Specific technology plans are overviewed including vibration diagnostics, model-based controls and diagnostics, advanced instrumentation, and general aviation propulsion system health monitoring technology. Propulsion system health monitoring, in addition to engine design, inspection, maintenance, and pilot training and awareness, is intrinsic to enhancing aviation propulsion system safety.

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